Aerometric Measurement and Modeling of CO_2 Flux from Crystal Geyser, UT: Implications for Health, Safety, and Environmental Consequences of CO_2 Leakage from a Deep Storage Site

Frank J. Gouveia, Mackenzie R. Johnson, Roald Leif, S. Julio Friedmann

UCRL-POST-210296

This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

Abstract:

Aerometric measurement and modeling of the mass of CO_2 emissions from Crystal Geyser, Utah: Health and safety implications of a complete wellbore failure analog.

To address concerns regarding potential leakage of CO_2 from underground storage sites, appropriate analogs can serve to circumscribe likely scenarios for human health and safety. Crystal Geyser in eastern Utah is a rare, non-geothermal geyser that emits carbon dioxide gas in periodic eruptions. For this study, the amount of CO_2 emitted from this geyser is estimated through measurements of downwind CO_2 air concentrations modeled for atmospheric dispersion. Five eruptions of Crystal Geyser occurred during the 48-hour field study; pre-eruption emissions were also timed and sampled. Slow wind during three of the active eruptions conveyed the plume over samplers arranged in arcs 25 to 100 m away from the geyser. An analytical, straight-line Gaussian model matched the pattern of concentration measurements. This is the first application of Gaussian dispersion modeling to a CO_2 geyser of any type, and demonstrates the feasibility and value of future method applications. CO_2 emission rates were between 2.9 and 6.7 kg/s during eruption events and about 0.20 kg/s during the active pre-eruptive events, with sample peak concentrations never exceeding 12650 ppm (4000 ppm mean). Extrapolation of our limited field data estimates annual geyser CO_2 emission of 13,000 tonnes. Comparison of results to storage scenarios serves to constrain sequestration efficacy and potential health risks from wellbore failure. Preliminary analysis suggests that even extremely large and rapid escape of CO_2 at this well presents a negligible risk to human health and safety. Future study may show likely cases of wellbore failure will have fluxes much less than the Crystal Geyser analog.

Setting

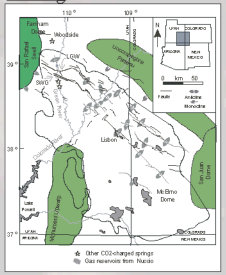
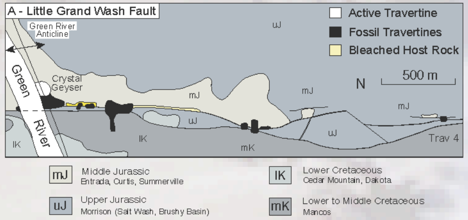


Figure 1: Location of Crystal Geyser. (Shipton *et al.*, 2004)

Crystal Geyser is located in southeastern Utah near the town of Green River (see Figure 1). The geyser erupts out of a well casing of a 1935-1936 hydrocarbon exploration well drilled to a depth of ~800 m. Before encountering bedrock, the drilling company drilled through ~21.5 m of tufa deposits, indicating that CO_2-charged waters effused from this location prior to the well being drilled. Other natural cold-water geysers are located in this area of Utah, most of which are probably fed by CO_2 charged waters stored in the Jurassic Navajo Sandstone, which is ~200 m below the surface at the well-site.

Figure 2: Generalized geologic map of field area. (Shipton *et al.*, 2004)



The occurrence of numerous travertine deposits in this region is likely related to flow of CO_2-rich brines to the surface. The locations of the Geyser and tufa layers reflect structural controls, such as fault intersections and the junctions of regional faults with fold axes (Figure 2). Similar ancient travertine deposits are found locally along the strike of the Little Grand Wash Fault. Researchers have been unable to definitively identify the source of the CO_2 for this region, but there is a consensus based on carbon isotope signatures that the CO_2 must originate either below or within the Paradox evaporites.

Objectives

Our goal was to combine downwind CO_2 concentrations with meteorological data to constrain the amount of CO_2 emitting from the Geyser during an eruption. This research was intended to provide initial estimates of annual flux and credible maximum flux, with the expectation of future field data collection.

Sampling

We set-up 4 sampling arcs downwind of the Geyser at radial distances of 25, 50, 75, and 100 m from the main vent (See Figures 3 and 4). Three to five samplers were evenly spaced along each arc. These "grey box" samplers draw air continuously at a slow rate, allowing us to acquire integrated air samples. This array was effective for three eruptions, and one small pre-eruptive episode; for the fourth eruption sampled the wind was blowing away from the array, so we used a portable "blue box" sampler, which has a faster collection rate. We also used a blue box to sample points of special interest, for instance very close to the vent (Figure 5) and upwind for a background CO_2 measurement.

Figure 3: Sampling Arcs

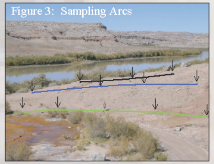


Figure 5: Blue box sampling of main vent during Eruption 3.

Photograph in Figure 3 was taken from the ridge east of the main vent. Here, the green, blue, and black curves trace the 50, 75, and 100 m arcs, respectively.

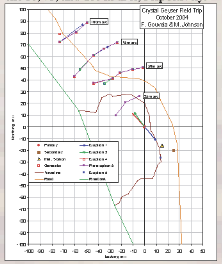


Figure 4 (above). Map of array. Solid arrows represent plume centerlines for E 1, 4 and 5* (red) and E3 (green) at 50 m and E5 (blue).

Observations

In addition to the samples and meteorological data, we recorded several parameters for each of the five eruptions that occurred during our 48- hour field deployment:

* Beginning, ending, and character of each eruption
* Nature and timing of the pre-eruptive activity

This allowed us to characterize the average eruption from Crystal Geyser:

* Eruption Duration Range: 7-25 minutes (Eruption 3 = 122 minutes)
* Typical Recharge Period: 5.75-6.25 hours (20 hours between E3 and E4)
* Pre-eruptive activity: Intensifies as an eruption becomes imminent

Analytical Methods

1) Gas chromatography of 152 air samples to obtain CO_2 concentrations in ppm.
2) Correlation of meteorological data with the eruption timing.
   a. Wind Speed and Wind Direction
   b. Air Temperature (and fluid temperature if probes were submerged) (See Figure 6)

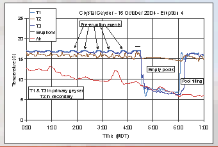


Figure 6: Temperature probe data from before and after Eruption 4. Plots similar to this allowed us to establish the timing of Eruption 2, which we did not directly observe. Temperature probe 2 was recording data from the peripheral vent.

Modeling Approach

We estimated the emission mass using a Gaussian dispersion model. Input parameters for the model include CO_2 concentrations, eruption timing, wind conditions, and sampler geometry. Tenets of the Gaussian dispersion model include (see Figures 7 and 8):

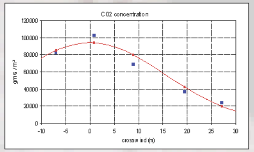
a. Calculate amount of CO_2 emitted according to

$$Q = \frac{2\pi\sigma_y\sigma_z u\chi}{E_y E_z}$$

σ_y and σ_z describe the plume size in the lateral and vertical dimensions, respectively;
u = the wind speed;
χ = product of the concentration multiplied by the amount of sampling time; and
E_y and E_z = factors to compensate for the samplers being located off the center line of the plume.

(Hanna *et al.*, 1982)

b. Estimate the plume width using a least-squares fit of the CO_2 data



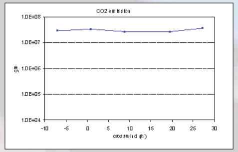


Figure 7 (left): Gaussian least-squares fit (red curve) to CO_2 concentrations (blue dots) measured along the 50-m arc during Eruption 3. Figure 8 (right): Calculated CO_2 emissions using the curve defined in Figure 7. Emission mass is calculated at every sampler location. The average is considered the best estimate for CO_2 emission.

Results

1) Models of the 50-m arc yielded the most consistent estimates (See Figures 7 and 8)
2) Emissions: (Estimates obtained from the 50-m arc data)
   a. ~1-5 tonnes of CO_2 per standard eruption
      * emissions from 2 hour eruption were 30× greater
   b. ~13,000 tonnes CO_2 per year

Table 1: Summary of eruption statistics.

Eruption	Date	Start time	End time	Duration	Recharge	Eruption Character
1	14-Oct	17:26:30	17:33:40	**0:07:10**	---	moderate
2	14-Oct	23:20:00	23:35:00	**0:15:00**	5:46:20	(na)
3	15-Oct	6:17:47	8:20:00	**2:02:13**	6:42:47	moderate
4	16-Oct	4:19:00	4:29:40	**0:10:40**	19:59:00	explosive
5*	16-Oct	9:45:00	9:56:40	**0:11:40**	---	(pre-eruptive)
5	16-Oct	10:41:30	11:06:00	**0:24:30**	6:11:50	moderate

Table 2: Plume shape and CO_2 emissions from modeling data collected along the 50 m arc.

Eruption	Centerline Angle	u (m/s)	σ_y (m)	σ_z (m)	Q (tonnes)	Q (kg/s)
1	138	0.9	24.9	12.5	**2.8**	**6.5**
3	144	1.2	15.9	8	**46**	**6.5**
4	138	0.8	16.6	8.3	**1.8**	**2.9**
5*	138	2.1	18.2	9.1	**0.16**	**0.19**

Table 3: Plume shape and CO_2 emissions from modeling data collected from locations other than the 50 m arc.

Eruption	Arc	Centerline Angle	u (m/s)	σ_y (m)	σ_z (m)	Q (tonnes)	Q (kg/s)
3	75	144	1.2	24.7	12.4	**31**	**4.2**
3	100	144	1.2	21.8	10.9	**14**	**2**
4	75	133	0.8	23.6	11.8	**1.3**	**2.1**
4	100	128	0.8	21.8	10.9	**0.38**	**0.6**
5*	25	138	2.1	9.8	4.9	**0.16**	**0.19**
5*	75	138	2.1	55.2	27.6	**0.86**	**1.1**
5*	100	138	2.1	21.6	10.8	**0.14**	**0.17**
5	30	320	2	10.5	5.3	**4.6**	**3.1**

Water sampling at main vent immediately prior to Eruption 5. The water around the base of the geyser is the rapid bubbling typical of pre-eruptive events that resemble the "rolling boil" of a kettle. Note the tape measure attached to the south side of the geyser casing.

The highest measured concentration of CO_2 during any of the events was **12,625** ppm, well below the level of harmful health effects. Average concentration during eruption was ~4000 ppm (median ~ **3200** ppm). This strongly suggests that even in extreme cases of CO_2 escape from wells, it is difficult to attain concentrations harmful to human health.

Technical Implications

Gaussian dispersion modeling, a widely accepted tool for modeling atmospheric dispersion, provides an advantageous approach to modeling CO_2 leaks:

1) It is inexpensive and easily adaptable to variable terrain and fluctuating wind conditions;
2) Plume width and centerline are objectively measured;
3) Modeling avoids bias from undersampling or oversampling of plume.

Environmental, Health and Safety Implications

1) Preliminary estimates suggest that maximum annual leakage rates are within the bounds of those discussed in association with multi-million tonne/year injections.

2) Concentrations of CO_2, even during maximum eruption rates, were less than 12,600 ppm and never reached levels dangerous to human health. This suggests that leakage from wells represents a limited HSE risk, one that can be readily recognized and managed.

3) Real leakage rates likely would be substantially less than the emissions rates measured at Crystal Geyser.

Acknowledgments and References

The authors would like to thank Ron Pletcher and Garrett Keating for their support and early involvement.

All photos by Frank Gouveia except: background (www.tcd.ie/Geology/ STAFF-PAGES/Fluids.html), upper left (http://www.uweb.ucsb.edu/~glennon/crystalgeyser/) and upper right (www.4x4now.com/cg.htm) adjacent to title.

Baer, J. L. and Rigby, J. K. 1978. Geology of the Crystal Geyser and the environmental implications of its effluent, Grand County, Utah. Utah Geology, 5, 125-130.

Shipton, Z.K., Evans, J.P., Kirschner, D., Kolesar, P.T., Williams, A.P., and Heath, J. 2004. Analysis of CO2 leakage through "low-permeability" faults from natural reservoirs in the Colorado Plateau, east-central Utah. In: Baines, S.J. and Worden, R.H. (eds.). Geological Storage of Carbon Dioxide. Geological Society, London, Special Publications, 233, 43-58.

Hanna, S.R., G.A. Briggs, and R.P. Hosker, 1982: Handbook on atmospheric diffusion. DOE/TIC-11223, Technical Information Center, U.S. Department of Energy.